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DEVELOPMENTS IN ELASTIC WAVE PROPAGATION IN CYLINDRICAL SHELLS

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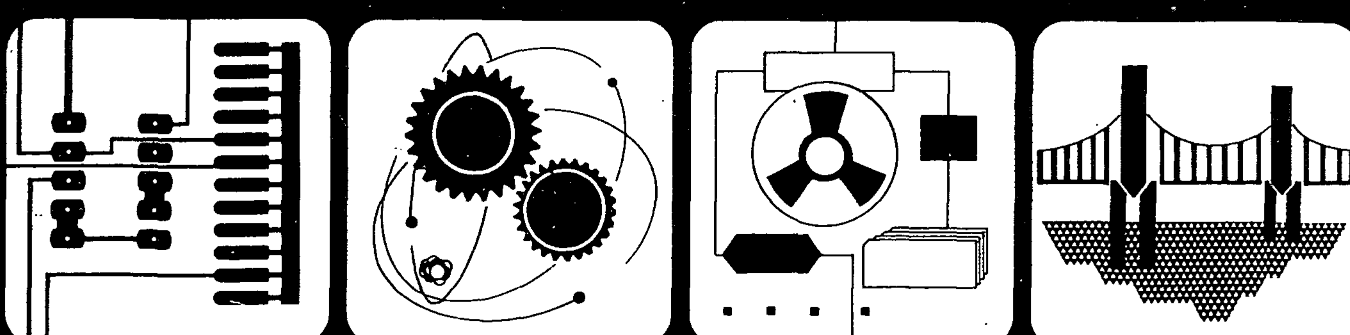

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The study of elastic stress wave propagation in bars and shells has received a multitude of effort in recent years. This literature review will deal specifically with longitudinal wave propagation. Before introducing the cylindrical shell literature, a brief review of longitudinal elastic wave propagation in circular bars will be presented as background information. It will be briefly reviewed because the approach to cylindrical shells follows a similar pattern. Perhaps the classical work in wave propagation in circular bars was done by Pochhammer (1) in 1876. His theoretical treatment is called the "exact" theory, and comes from the linear theory of elasticity with stress free surfaces generating frequency dependent solutions.

Further contributions to this area have been mainly from approximate theories and experimental studies. Comparison is usually made between the "exact" and approximate theories to determine the degree of accuracy. Usually the approximate theories are limited in application and are only applicable over certain frequency ranges.

Davies (2) has shown that for moderately high frequencies the faster traveling low frequency long waves from the lowest mode could account for the important features of the transient disturbance at stations on the bar removed from the input.

Other approaches to this problem recently have involved transform techniques, semi-infinite bars, and stationary phase methods. Skalak (3) investigated the longitudinal impact of a semi-infinite circular elastic

bar by using the equations of motion of linear elasticity theory and applying double integral transforms. He evaluated the inverse by using asymptotic approximations that were valid for large time after the initial impact. His results showed the long waves from the lowest mode formed the main contribution, agreeing with Davies (2), and an oscillation occurring about that contribution.

Redwood (4) has considered the propagation of a high frequency compressional pulse applied to the end of a semi-infinite bar. His high frequency approximation predicted a main signal propagating with a train of equally separated attenuating signals behind it.

McSkimin (5) has also considered the propagation of high frequency longitudinal pulses in cylindrical rods. He investigated mode conversion effects and approximated the resulting loss. Experimental results on fused silica are also cited.

Other contributions to this area have been made using various approximations. Some of these are discussed in Miklowitz (6) who provides a good list of references of work done before 1960.

The developments arising from analyses of cylindrical shells have followed a similar pattern as those concerning analyses of bars. They, of course, are more complex due to the presence of the interior free surface.

Ghosh (7) considered the exact theory with solutions of the wave train type. More recently Herrmann and Mirsky (8) completed a similar analysis. The results for the fundamental mode indicate that for wavelengths very long compared to the radius, the cylindrical shell behaves lika a solid rod, while for wave lengths very short compared to the radius it behaves like a plate, and wave lengths very short compared to the wall thickness

propagate with the Rayleigh surface wave speed. Heimann and Kolsky (9) have also investigated the exact theory in order to shed additional light on the applicability of the previous investigations. Their main contribution was the discovery of symmetrical plate waves.

There have been numerous approximate shell theories, each of which has application over a certain frequency range or shell thickness. The general desire, however, as in the case of plates, has been to establish a theory that can be used to model more accurately the higher frequency waves. For axially symmetric motion Herrmann and Mirsky (8) and Lin and Morgan (10) considered a Timoshenko thin shell theory which included membrane, bending, rotatory inertia, and transverse shear effects. They discovered that for long wave lengths the shell could accurately be treated as a membrane, but, as the frequency became higher additional effects had to be added. They also noted that neglecting rotatory inertia did not significantly change from the exact result. Naghdi and Cooper (11) included rotatory inertia and shear deformation effects, beginning with a thin shell theory of Love and Donnell. Their results were very similar to previous investigators. Junger and Rosato (12) considered a shell theory including membrane and bending effects. Their results agreed well with experimental results at long wave lengths but should not be expected to be accurate for higher frequencies. Mirsky and Herrmann (13) extended their previous work (8) to a thick shell by accounting for the additional effect of transverse normal stress. They found the lowest mode of the theory compared very favorably with the corresponding exact theory mode for practically all thicknesses. A good review of work done before 1960 can be obtained from either Miklowitz (6) or Redwood (14).

Johnson and Widera (15) used asymptotic integration schemes similar to earlier static shell solutions by Reissner (16) and extended them to produce a dynamic theory of cylindrical shells. Their results gave similar results to Herrmann and Mirsky (8) and Mirsky and Herrmann (13) but included additional modes. Some agreement was also noted with the investigations of Green and Naghdi (17).

Berkowitz (18) employed an approach similar to Skalak (3) to treat the longitudinal impact of a semi-infinite membrane cylindrical shell. He used integral transforms and asymptotic expansions to arrive at a solution which is only possible for large times. His analysis revealed that the axial stress had an initial value which propagated with the plate wave speed. The axial stress then decayed rapidly and was followed by a gradual increase to the major signal which propagated with the bar wave speed.

Spillers (19) used the method of characteristics to solve the set of equations developed by Herrmann and Mirsky (8) for a semi-infinite cylindrical shell with a constant velocity applied to one end. He also investigated the membrane solution, and arrived at results for values of time up to one-fifth of the smallest value of time considered by Berkowitz (18).

Oline (20) conducted a similar analysis, but included plasticity effects. Some of his elastic results were at variance with those of Spillers (19). Chou (21) used the method of characteristics to solve a system of equations for the semi-infinite cylindrical shell which were written in terms of displacements. His solutions were obtained for the shell for values of time up to about one tenth of the smallest time considered by Berkowitz (18). His results also were at variance with Spillers (19),

and he attributed it to numerical instability of the latter.

Akin and Counts (22) investigated a semi-infinite cylindrical membrane using Laplace transforms and Viskovatoff's (23) method of continued fractions. Their method has the ability to provide a complete solution, valid for small and large values of time. The results agreed well with Chou (21) and Berkowitz (18).

Malyshev (24) has investigated the response of a thin walled cylindrical shell to an axisymmetric step force on one end. He used membrane shell theory. He was reluctant to use the computer as did Spillers (19), and his closed form results were not limited to large time asymptotic solutions as Berkowitz (18). His results agree favorably with the previous results of the latter.

Chong, Lee, and Cakmak (25) investigated the response semi-infinite cylindrical shells subject to a pressure step loading, based on a one dimensional approximate theory of McNiven, Shah, and Sackman (26). They used double integral transforms and asymptotic solutions were obtained. Of particular interest was the discovery that for thin cylinders the maximum group velocity of the radial mode is slightly higher than the extensional mode.

Ometsinskaia (27) made the following observations after an analysis of non-classical shell theory, formed by a power series method. He found the results to have an extended domain of application as compared with the equations of classical theory, and in the description of the fundamental dispersion curve to be valid for short wavelengths commensurate with the shell thickness. His method, however, was less satisfactory in describing the higher order dispersion curves.

Saksonov (28) recently has completed a study of wave propagation in cylindrical shells. His result was based on a method proposed by Kil'Chevskii (29). Comparison of results of this study were within a few percent of those of Herrmann and Mirsky (8), but did not entail the introduction of the shear coefficient.

Mortimer, Chou, and Kiesel (30) have developed a new set of linear dynamic equations for shells of revolution which include effects due to membrane, bending, transverse shear deformation, rotary inertia, and large thickness. The set of equations are conveniently hyperbolic, thus facilitating a method of characteristics solution.

A finite difference numerical solution developed by Thorne and Herrmann (31) can handle motion in two dimensions. In addition to elastic behavior it can also accommodate elastic-plastic and hydrodynamic material behavior.

Counts and Bennett (32) have considered both finite and semi-infinite membrane cylindrical shells subjected to stress-pulse input using a dynamic finite element technique. The results show good agreement with Akin and Counts (22) and Berkowitz (18) for semi-infinite membrane cylindrical shells. One positive aspect of this method is the simpleness of handling reflections.

Only a few experimental programs have given any pertinent information as to how well the theoretical solutions model the real situation. Fitch (33) verified some work of Gazis (34) with experiments on 5052 aluminum-alloy cylinders. Wambold and Ju (35) using an analog simulation technique and a Tresca failure theory predicted impact speeds for failure of capped hollow cylinders. This was compared to some experimental work done at Sandia Corporation. Mortimer, Rose, and Chou (36) have experimentally conducted some

tests to determine the response of longitudinally impacted cylindrical shells. The experimental results of this study indicated that the wave front, after traveling about three diameters from the impacted end, propagated at essentially the plate velocity. Comparisons of experimental results were compared to a method of characteristics solution for bending and membrane theory with the conclusion that, for the size of cylinders tested, the membrane theory can be confidently used in analyzing the transient response of cylindrical shells.

Goldsmith, Lee, and Sackman (37) have recently conducted an experimental investigation of pulses propagating in circular tubes and compared these results to a numerical solution. The numerical scheme used a one-dimensional analysis which included a lateral inertia correction term. The general conclusions drawn were that pulse dispersion and attenuation were more prominent in shells than in corresponding sized elastic bars. The comparison of the theoretical and experimental results correlated well. Bending waves were also produced in the experiments which were found to travel about 47 percent that of the longitudinal components.

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